CLOUD-CLIMATE INTERACTIONS ON VENUS. M. A. Bullock and D. H. Grinspoon, Laboratory for Atmospheric and Space Physics, CB 392, University of Colorado, Boulder, CO 80309-0392. bullock@sunra.colorado.edu; david@sunra.colorado.edu.

Although it is well established that an intense greenhouse effect operates on Venus, our understanding of radiative processes in Venus' atmosphere is incomplete. The Pioneer Venus probes provided a wealth of data on the composition, temperature and pressure structure of the atmosphere as well as the mass and structure of the globally encircling cloud layers. These data enabled the development of relatively sophisticated two-stream radiative transfer models to explain the extraordinarily high surface temperature of Venus [1]. More recent developments from ground-based observations, laboratory spectral data, the Galileo NIMS instrument, and the Magellan mission have added incrementally to our understanding of the Venus climate system.

One of the most striking discoveries was that of excess radiation at 1.74 and 2.3 um on the nightside of Venus, which has been identified as thermal radiation passing through IR windows between strong absorption bands of CO_2 and H_2O [2]. The discovery of additional windows at wavelengths of 1.10, 1.18, 1.27 and 1.31 um have allowed for the ground-based exploration of the lower scale heights of Venus' atmosphere. Sophisticated radiative transfer modeling of high resolution spectra from the IRTF and AAO have yielded the retrieval of the abundances of key radiative species in the deep atmosphere [3-6]. In particular, these data and subsequent modeling efforts have indicated that H_2O abundances in Venus' atmosphere are at least 6 times lower than those interpreted from the Pioneer Venus data. Since H_2O is the most potent absorber, per molecule, in Venus' atmosphere, these results have major implications for our understanding of both the clouds and the greenhouse effect. Complementary to this improved understanding are vast improvements in spectral data bases. High temperature spectral data for H_2O and CO_2, available now in the HITEMP database [7] have yet to be employed in radiative flux models of Venus' greenhouse effect.

Galileo NIMS observations showed that near IR thermal emission in the window regions is spatially variable. This variability has been attributed to patchiness in the clouds [8]. Clouds act essentially as neutral density filters in each window region, yet contrast varies between the regions showing less spatial variability in the shorter wavelength windows and higher contrasts in the longer wavelength windows. An understanding of cloud structure spatial and temporal variability will allow for the improved modeling of the global radiative balance and the role played by the main cloud decks.

Volcanism is a primary driver of atmospheric compositional change on the Earth, where source functions are fairly well known. Before Magellan, however, we could only speculate on the volcanic history of Venus. UV spectroscopic measurements [9] showed approximately an order of magnitude decrease in cloud top SO_2 abundances from 1978 to 1983. It was suggested that this temporal variability could have been the result of major volcanic activity prior to Pioneer Venus, but global image coverage of the planet was not yet available. Continual analysis of the stratigraphy and impact cratering record, as revealed by Magellan is providing a picture of widespread and perhaps episodically intense volcanism in Venus' history. This enables us to constrain the source functions for radiatively important species in the atmosphere over time, a key driver of climate and clouds.

These recent developments have allowed us to construct a versatile one-dimensional model of radiative transfer in Venus' atmosphere that incorporates substantially more physics than previous models. Gaseous opacities are determined from line-by-line calculations of high temperature spectral data for CO_2, H_2O, HDO, SO_2,CO, HCl, COS, HF and H_2S. These are tabulated for a wide range of pressures and temperatures as k-distribution absorption coefficients. The k-coefficients are then convolved by mixing ratio and interpolated in temperature and pressure for each atmospheric layer. This scheme allows us to rapidly calculate opacities in atmospheric layers of arbitrary path lengths, mixing ratios, pressures and temperatures. Rayleigh scattering in the thermal IR by CO_2 and N_2 is a significant source of opacity in the lower atmospheric scale heights, and is therefore included in the model. Pressure induced continuum opacities due to CO_2 [10] and H_2O [11], important in Venus' dense atmosphere, are also calculated. Scattering due to sulfuric acid aerosols in Venus' cloud and haze layers is treated using laboratory optical data [12] and standard mie theory. Infrared fluxes are calculated using a hemispherical mean two-stream algorithm [13], which permits the rapid calculation of IR heating rates. Radiative equilibrium solutions are found using a time-adaptive iteration scheme that allows the radiative state of the atmosphere to relax to steady-state. A convective adjustment is then made to the temperature structure by setting the atmospheric lapse rate equal to the local adiabat wherever the radiative lapse rate exceeds it. The effects of clouds on the radiative balance of Venus' atmosphere are addressed by combining cloud microphysical calculations with a recent cloud chemistry model [14] that has been successful in explaining the OCS and CO profiles in the Venus atmosphere. The chemistry model solves the diffusion and condensation of H_2SO_4 and H_2O in Venus' cloud layers, and is well-suited for incorporation into an evolutionary radiative transfer model of Venus' atmosphere.

Previous models of the climate evolution of Venus [15] indicated a climate instability due to feedback between radiative-convective equilibrium and surface/atmosphere interactions. However, cloud albedo feedback and stability probably play a major role in the stability of Venus' climate. With the current more detailed radiative transfer model of Venus' atmosphere and clouds, we are in a position to address the following questions about climate on Venus:

1. What is the response of the Venus atmosphere-cloud system to perturbations in the abundance of H_2O, SO_2 and solar flux?

2. What are the changes in radiative and cloud processes in the atmosphere when volcanic sources of volatiles are continually or episodically active?

3. How much H_2O has to be removed from Venus' atmosphere before the clouds go away? What are the changes to climate that may result?

4. What levels of volcanism were necessary to create the current massive cloud system? If this happened or is happening, what were past climates on Venus like?

5. How does the climate equilibrate after an impact of a large comet, which could double the current amount of H_2O in Venus' atmosphere?

6. Is it possible for Venus to have experienced an even hotter climate in the past, raising surface temperatures to above the solidus for salt-rich lavas or even silicates?

Preliminary results from our radiative transfer model will be reported, and an assessment of the effects of various sources of opacity in Venus' atmosphere will be given. The prospects for answers to the above intriguing questions on cloud-climate interactions on Venus will be discussed.

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